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## DEVELOPMENT OF BIOMECHANICAL MODELS FOR HUMAN FACTORS EVALUATIONS

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### ABSTRACT

Previewing human capabilities in a computer-aided engineering mode has assisted greatly in planning well-designed systems without the cost and time involved in mockups and engineering models. To date, the computer models have focused on such variables as field of view, accessibility and fit, and reach envelopes. Program outputs have matured from simple static pictures to animations viewable from any eyepoint. However, while kinematics models are available, there are as yet few biomechanical models available for estimating strength and motion patterns. Those, such as Crew Chief, that are available are based on strength measurements taken in specific positions. Johnson Space Center is pursuing a biomechanical model which will use strength data collected on single joints at two or three velocities to attempt to predict compound motions of several joints simultaneously and the resulting force at the end effector. Two lines of research are coming together to produce this result. One is an attempt to use optimal control theory to predict joint motion in complex motions, and another is the development of graphical representation of human capabilities. This presentation describes the progress to date in this research.

### COMPUTER MODELING OF HUMAN MOTION

Computer aided design (CAD) techniques are now well established, and have become the norm in many aspects of aerospace engineering. They enable analytical studies, such as finite element analysis, to be performed to measure performance characteristics of the aircraft or spacecraft long before a physical model is built. However, because of the complexity of human performance, CAD systems for human factors are not in widespread use. The purpose of such a program would be to analyze the performance capability of a crew member given a particular environment and task. This requires the design capabilities to describe the environment's geometry and to describe the task's requirements, which may involve motion and strength. This in turn requires extensive data on human physical performance which can be generalized to many different physical configurations. PLAID is developing into such a program.

Begun at Johnson Space Center in 1977, it started out to model only the geometry of the environment. The physical appearance of a human body was generated, and the tool took on a new meaning as fit, access, and reach could be checked. Specification of fields of view soon followed. This allowed PLAID to be used to predict what the Space Shuttle cameras or crew could see from a given point. An illustration of this use is shown in Figures 1a and 1b. Figure 1a was developed well before the mission, to show the planners where the EVA astronaut would stand while restraining a satellite manually, and what the IVA crewmember would be able to see from the window. Figure 1b is the view actually captured by the camera from the window. However, at this stage positioning of the human body was a slow, difficult process as each joint angle had to be specified in degrees.

### REACH

The next step in enhancing PLAID's usefulness was to develop a way of positioning bodies by computer simulation, rather than by the engineer's inputs of joint angles. The University of Pennsylvania was contracted to perform this work. Korein (1985) developed an inverse kinematic solution for multijointed bodies. This enabled the engineer to position one "root" of the body (feet in foot restraint, or waist or hips fixed) in a specified location, and then specify what object or point in the workspace was to be touched by other parts of the body (such as place the right hand on a hand controller, and the left on a specific switch). The algorithm then attempted to find a position which would allow this configuration to be achieved. If it was impossible to achieve, due to shortness of arms or position of feet, a message would be presented giving the miss distance. This feedback enabled the engineer to draw conclusions about the suitability of the proposed body position and workspace. While this reach algorithm is extremely useful for body position, it does not enable an analyst to check an entire workspace for accessibility without specifying a large number of "reach to" points. This need has been recently met by a kinematic reach algorithm. The user specifies which joints to exercise. The algorithm then accesses an anthropometry data base giving joint angle limits, positions the proximal joint at its extreme limit,

and steps the distal joint through its range of motion in a number of small steps, generating a contour. The proximal joint is moved an increment, and the distal joint swung through its range of motion again. This process continues until the proximal joint reaches its other extreme limit. A three dimensional set of colored contours is thus generated which can be compared to the workstation and conclusions can be drawn. An example of this is shown in Figures 2a and 2b.

In Figure 2a, a fifth percentile female is placed at the proposed foot restraint position intended to provide an eyepoint 20" from the workstation. In this position, her reach envelope falls short of the workstation. Figure 2b shows the same body and reach envelope positioned with a 16" eyepoint, in which case the woman can reach the workstation.

### ANIMATION

Human performance is not static. To do useful work, the crewmembers must move their hands at least, and frequently their bodies, their tools, and their equipment. While this can be captured in a sequence of static pictures, animations are much preferred because they show all the intermediate points between the static views. Originally, PLAID animations were created by having the analyst enter every single step individually. This was highly labor intensive, and prohibitive in cost for any but the most essential conditions. However, an animation capability was created that allowed the user to input only "key frames". (A key frame is one where the velocity or direction of motion changes.) The software then smoothly interpolates 20 or 30 intermediate frame scenes, showing the continuous movement. This has many applications for both the Shuttle program and for the Space Station Freedom (SSF) program. For example, in determining where interior handholds were needed, an animation was created showing the process of moving an experiment rack from the logistics module to the laboratory module. Clearances, collisions, and points of change could be identified from the videotape. However, while the tape showed the locations for the handholds, it could not give information as to the loads the handholds would have to bear. Thus a project to model strength was begun.

### BIOMECHANICS MODELING

#### Upper Torso Strength

Using a Loredan, Inc. LIDO dynamometer (Fig.3), single joint strength data was collected for the shoulder, elbow, and wrist of one individual. The data was collected in the form of (velocity, position, strength) triplets. That is, the dynamometer was set to a selected speed, ranging from 30 deg/sec to 240 deg/sec in 30 deg/sec increments. For that speed, the subject moved his joint through its entire range of motion for the specified axis (abduction/adduction, flexion/extension). Data was collected every five degrees and a polynomial regression equation fit to the data for that velocity. The velocity was changed, and the procedure repeated. This resulted in a set of equations giving torque in foot-pounds as a function of velocity and joint angle, for each joint rotation direction.

Figure 4 shows shoulder flexion torque over a range of angles, parameterized by velocity.

Figure 5 shows the data points and the equation fit for elbow flexion/extension over the range of motion at 90 deg/sec. These regression equations were stored in tables in PLAID. To predict total strength exerted in a given position or during a given motion, the body configuration for the desired position (or sequence of positions) is calculated from the inverse kinematics algorithm. For example, the task used so far in testing is ratchet wrench push/pull. This task is assumed to keep the body fixed, and allow movement only of the arm. (As more strength data is obtained, the tasks can be made more complex.) A starting position or the wrench is established, and the position of the body is set. The angles of the arm joints needed to reach the wrench handle are then calculated. A speed of motion, indicative of the resistance of the bolt, is specified. The tables are searched, and the strength for each joint, for the given velocity, at the calculated angle, is retrieved. The direction of the force vector is calculated from the cross products of the segments, giving a normal to the axis of rotation in the plane of rotation. Once all these force vectors are obtained, they are summed vectorially to calculate the resultant end effector force. Currently the program displays the force for each joint and the resultant end effector force, as illustrated in Figure 6. The ratchet wrench model rotates accordingly for an angular increment. This requires a new configuration of the body, and the calculation is repeated for this new position. A continuous contour line may be generated which shows the end effector force over the entire range of motion by color coding. The model will be validated this summer. A ratchet wrench attachment for a dynamometer has been obtained, and an Ariel Motion Digitizing System will be used to measure the actual joint angles at each point in the pushing and pulling of the wrench. This will provide checks on both the validity of the positioning algorithms and of the force calculations. When this simple model is validated, more complex motions will be investigated. The significance of this model is that it will permit strengths to be calculated from basic data (single joint rotations) rather than requiring that data be collected for each particular motion, as is done in Crew Chief (Easterly, 1989). A synthesis of the reach envelope generating algorithm and the force calculations has been achieved. The analyst can now generate reach contours which are color coded to show the amount of force available at any point within the reach envelope.

#### Effects of Gravity-Loading on Vision

Human vision is another important parameter being investigated in conjunction with human reach and strength. Empirical data relating maximum vision envelopes vs gravity loading have been collected on several subjects by L. Schafer and E. Saenz. This data will be tabularized in a computer readable form for use in man-modeling. Preliminary software design has begun on a vision model which will utilize this vision data to simulate a period of Space Shuttle launch where gravity loading is a major factor.

This model will be able to dynamically display the vision cone of a particular individual as a function of gravity force and project that cone onto a workstation to determine if all the appropriate gauges/ displays can be seen.

#### APPLICATIONS

The biomechanical models, combined with geometric and dynamic modeling of the environment, have two major applications. The first is in equipment design. Frequently the strength or force of a crewmember is a key parameter in design specifications. For example, a manually operated trash compactor has recently been built for the Shuttle for extended duration (10-14 days) operations. This is operated by a crew member exerting force on the handle to squeeze the trash, and is seen as an exercise device as well as a trash compactor. The two key specifications needed were: how much force can a relatively weak crewmember exert, so the right amount of mechanical amplification can be built in; and how much force could a very strong crewmember exert, so the machine could be built to withstand those forces. When the biomechanical model is completed, questions such as these can be answered during the design phase with a simulation, rather than requiring extensive testing in the laboratory. In addition, the size of the equipment can be compared visually to the available storage space, and the location of foot restraints relative to the equipment can be determined. Other equipment design applications include determining the specifications for exercise equipment, determining the available strength for opening or closing a hatch or door, and determining the rate at which a given mass could be moved. The second application for a strength model is in mission planning. Particularly during extravehicular activities (EVA), crewmembers need to handle large masses such as satellites or structural elements. A complete dynamics model would enable the mission planners to view the scenes as they would be during actual operations, by simulating the forces which can be exerted and the resulting accelerations of the large mass.

#### FUTURE PLANS

Currently the only motion modeled is a rotational motion of a wrench using only the arm, not the entire body. One step in developing a useful model is to allow the software already available for animating motion to be used to define any motion and then permit calculation of the strength available, taking the entire body into account. This is a major step to accomplish, because of the many degrees of freedom in the entire human body. Research at the University of Pennsylvania has investigated the use of "comfort models" for predicting path trajectory. Badler, Lee, Phillips, and Otani (1989) have discussed in some detail the effects that varying weights have on trajectories for moving an object from one point to another. Using the Ariel tracking system, this hypotheses can be tested in the lab. In order to consider the entire body in strength analysis, empirical strength data must be collected. The Anthropometry and Biomechanics Lab at Johnson Space Center is beginning work on this project. To

date, shoulder and arm strength measurements have been collected on a number of subjects. This data must be made available through the program's data base so that 5th percentile, or median, or 95th percentile strengths can be examined. This will involve another layer of data in the data base. The strength measurements for the entire body, especially torso and legs, are needed. Collecting these strength data for the individual joints at a number of angular positions and angular velocities will be an ongoing project for some time. However, efforts have been made to automate data entry and reduction, which will result in easier data collection. Finally, the most important step is to validate the strength data. An assembly for collecting forces and angles for a ratchet wrench operation is available, and will be used to validate the compound motion of the arm. Movement of the entire body will be validated after the original data is collected, equations fit, and predictions of strength made.

#### BIBLIOGRAPHY

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Easterly, J. "CREW CHIEF: A Model of a Maintenance Technician", AIAA/NASA Symposium on the Maintainability of Aerospace Systems, July 26/27, 1989; Anaheim, CA.

Korein, James U. 'A Geometric Investigation of Reach', MIT Press, Cambridge, MA; 1985.

ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH

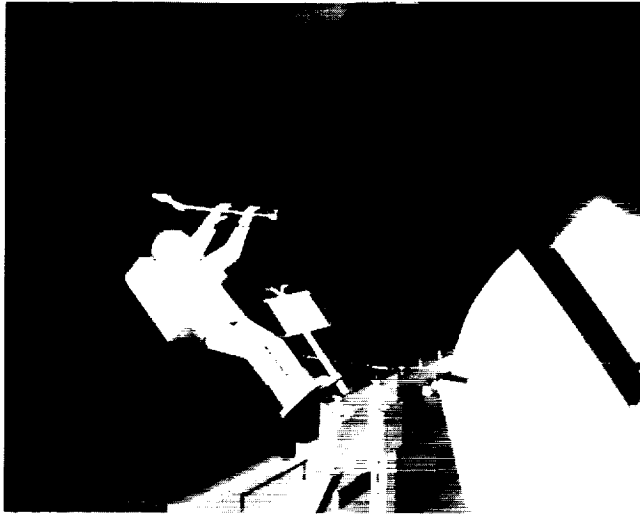


Figure 1a. PLAID rendition of crewmember restraining payload, from pre-mission studies.

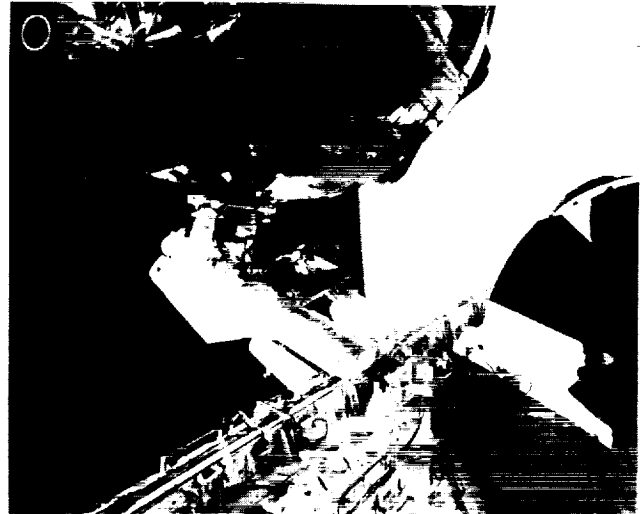


Figure 1b. Photo taken during mission from aft crew station.

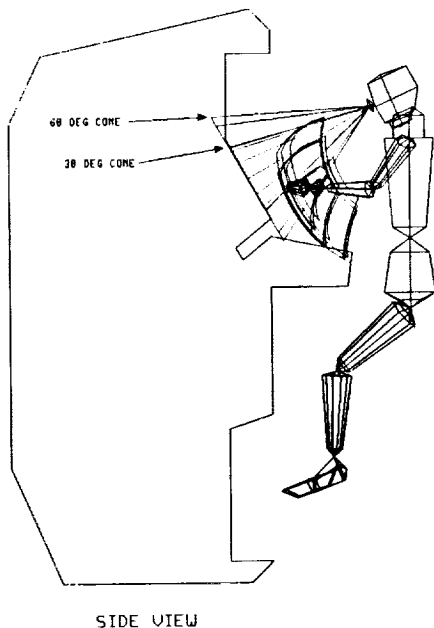


Figure 2a. Fifth percentile female positioned at workspace with 20" eyepoint. Reach contours miss the workstation.

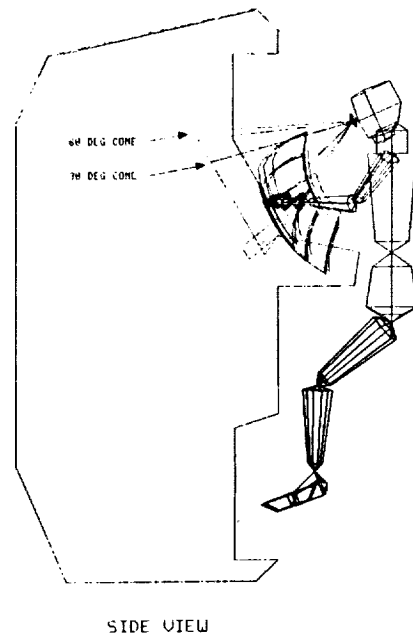


Figure 2b. Fifth percentile female positioned at workspace with 16" eyepoint. Reach contours touch workstation.



Figure 3. Collecting shoulder strength data with LIDO dynamometer.

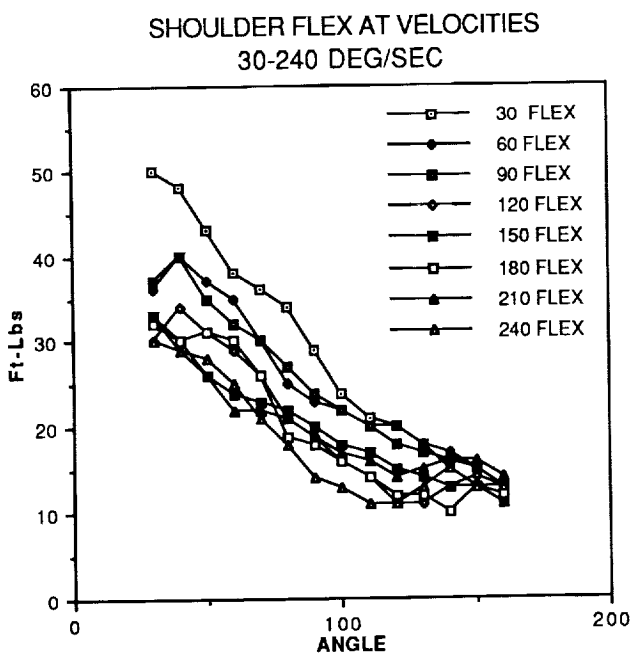


Figure 4. Shoulder flexion torque for velocities ranging from 30°/sec to 240°/sec

#### ELBOW FLEX/EXT 90 DEG/SEC

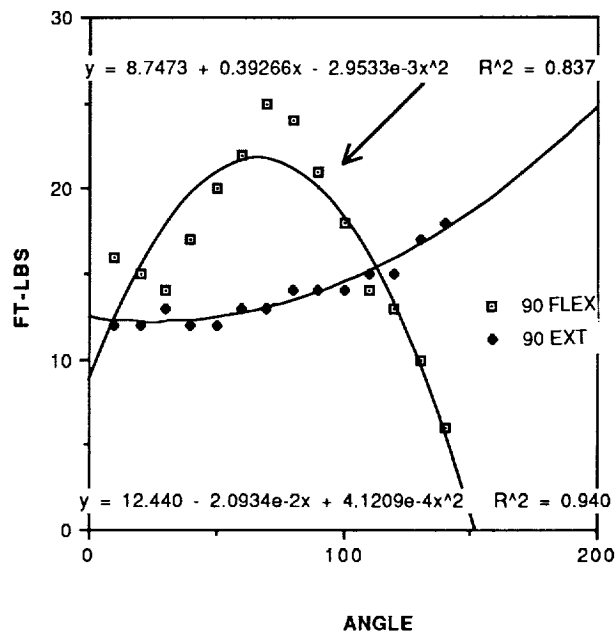


Figure 5. Raw data and regression equations for elbow flexion and extension at 90°/sec.

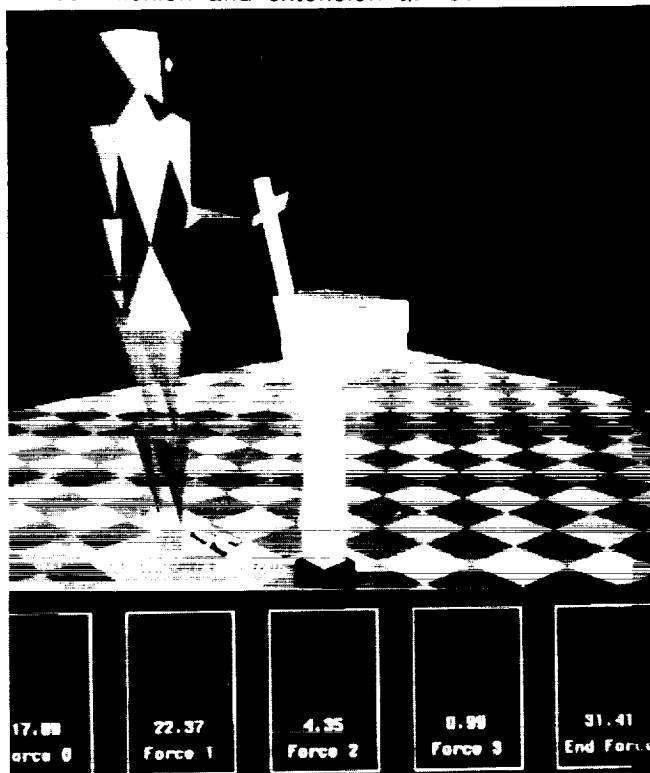


Figure 6. Body model exerting force on ratchet wrench. Joint forces and effective force at wrench are displayed as bar graphs beneath the picture.